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Spin current polarization and electrical conductivity in metal helimagnets

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Abstract. The peculiarities of spin and charge kinetics in helical magnetic metals that are due to forces acting on the magnetic moment of conduction electrons in inhomogeneous magnetic field have been considered. Analyzing the equations of motion for non-equilibrium spin density shows that an electric field directed along the axis of the helix produces conduction-electron spin polarization along this direction. Under the same conditions, the directions of polarization of the spin current and polarization of the locally equilibrium spin density are collinear. The specific structure of the effective exchange field acting on the conduction electrons in helical magnets causes two additional spin relaxation mechanisms to emerge. In addition to the mechanism of spin-lattice relaxation, “diffusion” and “precession” mechanisms of spin relaxation exist in conductive helical magnets. The diffusion mechanism is analogous to the Dyakonov-Perel spin relaxation mechanism. The key point is that the inhomogeneities of a magnetic field initiate a coupling between the spin and charge systems. It has been shown that, in a helical metal, the electrical conductivity decreases due to the action of the non-uniform exchange magnetic field.

1. Introduction

The subject of the research is the spin-dependent transport properties of conductive helimagnets. We focus on the peculiarities of charge and spin kinetics that arise due to the action of forces acting on the magnetic moment of conduction electrons in an inhomogeneous magnetic field.

The paper [1] is one of the first works to discuss the relationship between spin and charge kinetics in nonmagnetic conductors and chiral symmetry of the potential of spin-orbit interaction with impurities. It was found that the magnetization occurs proportionally to an electric field applied. The authors termed it “kinetic magnetoelectric effect”. The authors of [2], using a model of spin-density waves, showed that the kinetic magnetoelectric effect may exist in metallic antiferromagnets with a helical spin-density wave. They also emphasized that an appropriate correction to conductivity in such metals should be accounted for. In [3], the effect of spin polarization of electrons by a domain wall due to exchange interaction was studied in the frame of a phenomenological approach. The paper [4] is one of the recent works in which an attempt was made to describe electron transport in a medium with a helical magnetic structure. It interprets charge kinetics through the Boltzmann equation.

The present paper proposes a description of spin kinetics of magnetically inhomogeneous systems via a quantum kinetic equation for the quantum distribution function [5, 6]. Usage of the quantum kinetic equation makes it possible to take into account the relationship between the spin and charge kinetics in a relatively simple way [7]. The equations used were derived in [8].



2. Theory

The kinetics of electrons in inhomogeneously magnetized metals, including also conductive helical magnets, can be described through a system of equations of motion for the electron density $N(\mathbf{r}, t)$, the spin density $\mathbf{S}(\mathbf{r}, t)$, the electron flux density $\mathbf{I}(\mathbf{r}, t)$ and a tensor of the spin current density $\mathbf{J}(\mathbf{r}, t)$, with the system deriving from a quantum kinetic equation for the quantum distribution function [8]. To compose a quantum kinetic equation for conduction electrons in helical magnets, the exchange interaction between the electrons and the magnetic subsystem needs to be taken into account. This exchange interaction can be regarded as the action of the mean field of the localized spins on the spin of conduction electrons [3]. The field can be treated as the internal magnetic field $\mathbf{H}^{(\text{ex})}(\mathbf{r}, t)$.

The investigation covers helical magnets with the simple helical spin ordering; the axis of the helix is located along the OZ direction. The internal magnetic field of a simple magnetic spiral can be written as $\mathbf{H}^{(\text{ex})} = H^{(\text{ex})}(0)(\mathbf{e}_x \cos qz + K\mathbf{e}_y \sin qz)$, where $q = \frac{2\pi}{\lambda}$, λ is the helix period, $\mathbf{e}_x, \mathbf{e}_y$ are unit vectors along the OX and OY axes, $K = +1$ and $K = -1$ for right-handed and left-handed spirals, respectively. For simplicity, we leave aside the electron scattering asymmetry effects due to electron spin-orbit interaction with scatterers. A constant electric field \mathbf{E} is assumed to be directed along the axis of the spiral. In a steady state, at such a configuration of the fields, only components J_{zi} of the spin current density tensor are non-zero. Therefore, the spin current can be described far much simpler using the vector $\mathbf{P}_z = J_{zi}\mathbf{e}_i$ instead of the tensor \mathbf{J} . In what follows, this vector will be referred to as the spin current polarization vector. Under the conditions specified above, the quantum kinetic equation yields the following set of equations describing the kinetics of electrons in helical magnets in a linear approximation of the electric field:

$$\frac{\partial}{\partial z} I = 0, \quad (1)$$

$$\frac{\partial}{\partial z} \mathbf{P}_z + [\delta\mathbf{S} \times \boldsymbol{\Omega}_L] + \frac{1}{\tau_s} \delta\mathbf{S} = 0, \quad (2)$$

$$I = \frac{N_0 e \tau_p}{m} E - \frac{\tau_p \mu}{m} \delta\mathbf{S} \cdot \frac{\partial \mathbf{H}^{(\text{ex})}}{\partial z}, \quad (3)$$

$$\mathbf{P}_z = -D \frac{\partial}{\partial z} \delta\mathbf{S} + \frac{\tau_p e}{m} E \mathbf{S}_L - \tau_p [\mathbf{P}_z \times \boldsymbol{\Omega}_L], \quad (4)$$

where τ_p is the momentum relaxation time, τ_s is the spin relaxation time, D is the electron diffusion coefficient, N_0 is the equilibrium electron density, $\boldsymbol{\Omega}_L = \frac{2\mu}{\hbar} \mathbf{H}^{(\text{ex})}$, $e = -|e|$, m and μ are the charge, effective mass, and magnetic moment of an electron, respectively. The quantity $\delta\mathbf{S} = \mathbf{S} - \mathbf{S}_L$ in the equations (2)-(4) is the deviation of the spin density \mathbf{S} from its local equilibrium value $\mathbf{S}_L = -\frac{\chi}{\mu} \mathbf{H}^{(\text{ex})}$, where χ is the Pauli susceptibility.

We write down the vector equations (2) and (4) in the basis of mutually orthogonal unit vectors \mathbf{h} , \mathbf{h}' and \mathbf{k} , determined from ratios: $\mathbf{H}^{(\text{ex})} = H^{(\text{ex})}\mathbf{h}$, $\frac{\partial \mathbf{H}^{(\text{ex})}}{\partial z} = \left| \frac{\partial \mathbf{H}^{(\text{ex})}}{\partial z} \right| \mathbf{h}'$, $\mathbf{k} = [\mathbf{h} \times \mathbf{h}']$. The directions of the vectors \mathbf{h} , \mathbf{h}' and \mathbf{k} coincide with the directions of the magnetic field, the gradient of the magnetic field, and the direction of the spiral axis OZ , respectively. The chirality quantity K introduced above is the scalar product of the chirality vector \mathbf{k} and the unit vector \mathbf{e}_z , $K = \mathbf{k} \cdot \mathbf{e}_z$. Suppose that the length of the vector quantities $\mathbf{H}^{(\text{ex})}$, $\delta\mathbf{S}$, \mathbf{P}_z is preserved when moving along the helix. Consequently, we obtain that $\mathbf{P}_z \parallel \mathbf{h}$. So, the solution to equation (4) appears as:

$$\mathbf{P}_z = -D \frac{\partial}{\partial z} \delta\mathbf{S} - \chi \tau_p \frac{e}{m\mu} H^{(\text{ex})} E \mathbf{h}. \quad (5)$$

Taking equation (5) into account, we may rewrite equation (2) in the form:

$$-D \frac{\partial^2}{\partial z^2} \delta\mathbf{S} + [\delta\mathbf{S} \times \boldsymbol{\Omega}_L] + \frac{1}{\tau_s} \delta\mathbf{S} = \chi \tau_p \frac{e}{m\mu} H^{(\text{ex})} q E \mathbf{h}'. \quad (6)$$

Equation (6) allows one to calculate the non-equilibrium spin density $\delta\mathbf{S}$ and to represent it as the sum $\delta\mathbf{S}(z) = \delta\mathbf{S}^\perp(z) + \delta\mathbf{S}^\parallel$, where the indices \perp and \parallel indicate the direction of the vector relative to the axis of the helix (perpendicular and parallel, respectively):

$$\delta S^{\parallel} = \chi \left(\frac{1}{\tau_s} + \frac{1}{\tau_D} + \frac{1}{\tau_L} \right)^{-1} \tau_p \tau_s \frac{2e}{\hbar m} (H^{(ex)})^2 q E \mathbf{k}, \quad (7)$$

$$\delta S^{\perp} = \chi \left(\frac{1}{\tau_s} + \frac{1}{\tau_D} + \frac{1}{\tau_L} \right)^{-1} \tau_p \frac{e}{m\mu} H^{(ex)} q E \mathbf{h}'. \quad (8)$$

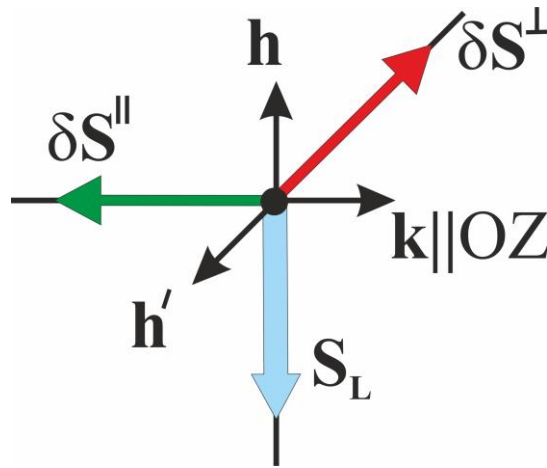


Figure 1. The arrangement of spin density vectors in the basis of \mathbf{h} , \mathbf{h}' , \mathbf{k} for positive values of the electric field. The figure is not to scale.

The quantity $\tau_D^{-1} = q^2 D$ is the inverse spin relaxation time, with the relaxation arising due to the diffusion motion of an electron along the axis of a helicoid when the electron spin «feels» a magnetic field changing in space. Taking into account the relation of diffusion coefficient and momentum relaxation time τ_p , $D = \frac{1}{3} v_F^2 \tau_p$, where v_F is the Fermi velocity, we can rewrite τ_D^{-1} as $\tau_D^{-1} = \Omega_D^2 \tau_p$, where $\Omega_D = q v_F / \sqrt{3}$. The quantity $\tau_L^{-1} = \Omega_L^2 \tau_s$ is the inverse spin relaxation time, with the relaxation in this case arising due to the precession motion of the nonequilibrium spin density. The diffusion mechanism of spin relaxation in helical magnets is analogous to the Dyakonov-Perel spin relaxation mechanism.

From equations (7) and (8) it follows that

$$\frac{|\delta S^{\parallel}|}{|\delta S^{\perp}|} = \Omega_L \tau_s. \quad (9)$$

The ratio of the longitudinal δS^{\parallel} and transverse δS^{\perp} components of the non-equilibrium spin density is determined only by the value of the parameter $\Omega_L \tau_s$. For weak exchange fields $H^{(ex)}$, for which $\Omega_L \tau_s \ll 1$, the longitudinal non-equilibrium spin density is small as compared with the transverse one, whereas in the case of strong fields, with $\Omega_L \tau_s \gg 1$, the electrons have a non-equilibrium spin density close to the longitudinal one.

The ratio between the transverse non-equilibrium spin density and the equilibrium spin density varies depending on the applied electric field. Since the electric current density can be expressed in the form $j = \sigma_0 E$, where $\sigma_0 = N_0 e^2 \tau_p / m$, the ratio of the absolute values of the transverse non-equilibrium spin density and the equilibrium spin density can be represented as

$$\frac{|\delta S^{\perp}|}{|S_L|} = \frac{j}{j_0}, \quad (10)$$

where $j_0 = \frac{N_0 e}{q} \left(\frac{1}{\tau_s} + \frac{1}{\tau_D} + \frac{1}{\tau_L} \right)$. If the value of j_0 is much larger than the maximum available current density for metals, δS^{\perp} is small compared with S_L .

From equation (7) it follows that in spiral magnets, an electric field applied along the spiral axis causes spin polarization of the conduction electrons along this axis. In [1, 2] this effect gained the name of kinetic magnetoelectric effect.

By analogy with the vector of the non-equilibrium spin density, the polarization vector of the spin current can be represented as the sum $\mathbf{P}_z(z) = \mathbf{P}_z^\perp(z) + \mathbf{P}_z^\parallel$. From equation (5) it follows that $\mathbf{P}_z^\parallel = 0$. The vector of the transverse spin-current polarization \mathbf{P}_z^\perp can be written as:

$$\mathbf{P}_z^\perp = -\chi \left(\frac{1}{\tau_s} + \frac{1}{\tau_D} + \frac{1}{\tau_L} \right)^{-1} \left(\frac{1}{\tau_s} + \frac{1}{\tau_L} \right) \tau_p \frac{e}{\mu m} H^{(ex)} E \mathbf{h}. \quad (11)$$

Therefore, the directions of the polarization vector of the spin current and the equilibrium spin density are collinear.

The system of equations of motion also makes it possible to calculate the current density $\mathbf{j} = e\mathbf{I}$ through the expression $j = [\sigma_0 - \Delta\sigma]E$, where $\sigma_0 = N_0 e^2 \tau_p / m$ and

$$\Delta\sigma = \frac{9}{4} \left(\frac{\mu H^{(ex)}}{\varepsilon_F} \right)^2 \frac{(qL_s)^2}{1 + (qL_s)^2 + (\tau_s \Omega_L)^2} \sigma_0, \quad (12)$$

where given that $\chi = \frac{3N_0 \mu^2}{2\varepsilon_F}$, ε_F is the Fermi energy and $L_s = \sqrt{D\tau_s}$ is the spin diffusion length.

From equation (12) it follows that the exchange magnetic field gradient decreases the conductivity of the metal studied compared with conductivity σ_0 of the same metal without a helix structure. The value of $\Delta\sigma$ depends on the parameters qL_s and $\tau_s \Omega_L$. The maximum possible value of ratio $\Delta\sigma/\sigma_0$ at any relation between the qL_s and $\tau_s \Omega_L$ parameters is determined by square of the ratio of exchange energy $\mu H^{(ex)}$ and Fermi energy ε_F :

$$\frac{\Delta\sigma}{\sigma_0} \leq \left(\frac{\mu H^{(ex)}}{\varepsilon_F} \right)^2. \quad (13)$$

In writing the original equation (4), we restricted ourselves to a linear approximation of the electric field. To complete the picture, the spin kinetics was calculated in the nonlinear approximation of the electric field. In this case, both the non-equilibrium spin density and the spin current polarization turn out to have the components directed along \mathbf{h} , \mathbf{h}' and \mathbf{k} . In the simplest case, the influence of nonlinear effects can be described by introducing an effective diffusion coefficient that is nonlinearly dependent on the electric field. The nonlinear components of the coefficient rise proportionally to the square of the field E . As a result, the spin diffusion length also increases. For metals, possible values of the electric field show that these effective quantities increase insignificantly and, therefore, formula (12) and the estimate correction (13) to the conductivity remain valid.

3. Evaluation and modelling

According to equation (13), numerical estimation of $\Delta\sigma/\sigma_0$ for metals with a typical value of ε_F of the order of 1eV and exchange energy $\mu H^{(ex)}$ in the range of (0.01 ÷ 0.1)eV gives $(\Delta\sigma/\sigma_0) \sim (10^{-4} \div 10^{-2})$. Therefore, the spin effects described above may have a noticeable magnitude and be observed experimentally.

For helical magnetic metals, the order of magnitude of the introduced spin relaxation times can be evaluated. Bearing in mind that $\tau_s \sim 10^{-10} \div 10^{-12}$ s, $\tau_p \sim 10^{-14}$ s, $q \sim 10^7 \div 10^9$ m⁻¹, $v_F \sim 10^6$ m/s, $\Omega_L \sim 10^{13} \div 10^{14}$ s⁻¹, we get the following estimates: $\tau_D = 10^{-12} \div 10^{-16}$ s, $\tau_L = 10^{-14} \div 10^{-18}$ s. The resulting order of the spin relaxation times indicates the possibility of experimentally observing the influence of the diffusion and precession mechanisms of spin relaxation by the effective spin relaxation time value.

The estimate of the ratios for the spin densities shows that $\frac{|\delta S^\parallel|}{|\delta S^\perp|} = 10^2 \div 10^5$ for helical metals. Therefore, the non-equilibrium spin polarization is always oriented along the helix axis. The magnitude of $j_0 = 10^{14} \div 10^{19} \frac{A}{m^2}$ significantly exceeds the maximum possible value of current density in metals. Hence, δS^\perp in helical metals is always small compared with the equilibrium spin density.

Expressions (7), (8) allow us to give a graphic illustration of the distribution of the magnetization $\mathbf{M} = -\mu\mathbf{S}$ in a helical magnet. For simplicity, consider the case of $\tau_D \gg \tau_L$ (for the case of $\tau_L \gg \tau_D$, the picture is preserved, only the numerical values of the magnetization change). For calculation, the following values are taken: $\chi = 10^{-6}$, $q = 10^9$ m⁻¹, $\tau_s = 10^{-10}$ s, $\mu H^{(ex)} = 0.01$ eV.

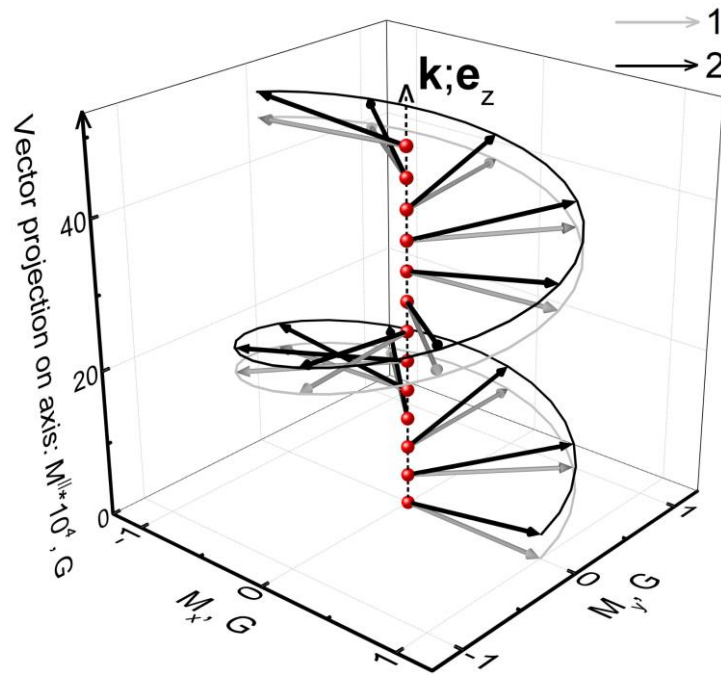


Figure 2. Magnetization of conduction electrons in a helical magnetic metal with a right-handed spiral (chirality is $K = +1$). The arrows correspond to the magnetization in a layer. The balls denote the arrangement of the layers in space along the OZ axis. The arrows are: 1 – equilibrium magnetization \mathbf{M}_L , 2 – non-equilibrium magnetization $\mathbf{M} = \mathbf{M}_L + \delta\mathbf{M} \cdot 10^4$. The magnitude of the applied electric field corresponds to the current density $j = 10^{10} \frac{\text{A}}{\text{m}^2}$.

Figure 2 demonstrates that the direction of the longitudinal component of magnetization is aligned with the chirality vector. A similar picture can be drawn for helical magnets with a left-handed helix (chirality is $K = -1$). Hence, an important conclusion follows: direct information on the chirality of the magnet can be provided through experimentally finding the direction of the longitudinal component of the magnetization of conduction electrons relative to the direction of the current density vector.

4. Conclusion

Spin and charge kinetics of conduction electrons in helical magnetic metals with the spin ordering of the “simple helix” type has been described. For this, a system of equations of motion, obtained from a quantum kinetic equation for the quantum distribution function, has been utilized. In a steady state when an electric field is applied along the axis of the helix, the equation of motion for the spin current density tensor is reduced to the equation for the spin current polarization vector. Analyzing the equations of motion for non-equilibrium spin density shows that an electric field directed along the axis of the helix produces conduction-electron spin polarization along this direction. It is shown that there is a relationship between the direction of the longitudinal magnetization of conduction electrons and the direction of chirality of the magnet. This property allows one to determine the chirality of the helical magnet by finding the direction of the longitudinal magnetization of conduction electrons relative to the direction of the current flowing along the helix axis. Namely, for right-handed helical magnets, the direction of the longitudinal magnetization coincides with the current density direction whereas for left-handed helical magnets, the direction of the resulting longitudinal magnetization is opposite to the current direction. Under the same conditions, the directions of the spin current polarization and the equilibrium spin density are collinear. It has been found that “diffusion” and “precession” mechanisms

of spin relaxation in helical magnets are observed. The diffusion mechanism of spin relaxation is an analogue of the Dyakonov-Perel spin-relaxation mechanism.

A complex structure of fields and their gradients in helical magnets plays an important role in charge kinetics. It has been established that a magnetic field gradient diminishes the electrical conductivity in a helical metal. A numerical estimate of the magnitude of the above reduction shows that it may have a noticeable magnitude and be observed experimentally.

The analysis of the spin kinetics in the nonlinear approximation of an electric field has been carried out. It should be noted that in this case the spin-current polarization has a longitudinal component. In the simplest case, the influence of nonlinear effects can be described in terms of the effective spin diffusion coefficient that is dependent on the electric field. Such a diffusion coefficient acquires an additive that increases proportionally to the square of the electric field. As a result, the effective length of the spin diffusion also increases. For possible values of the electric field in metals, these effective quantities rise insignificantly. Consequently, an estimate correction to the conductivity, performed in the linear approximation of the electric field, remains relevant.

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